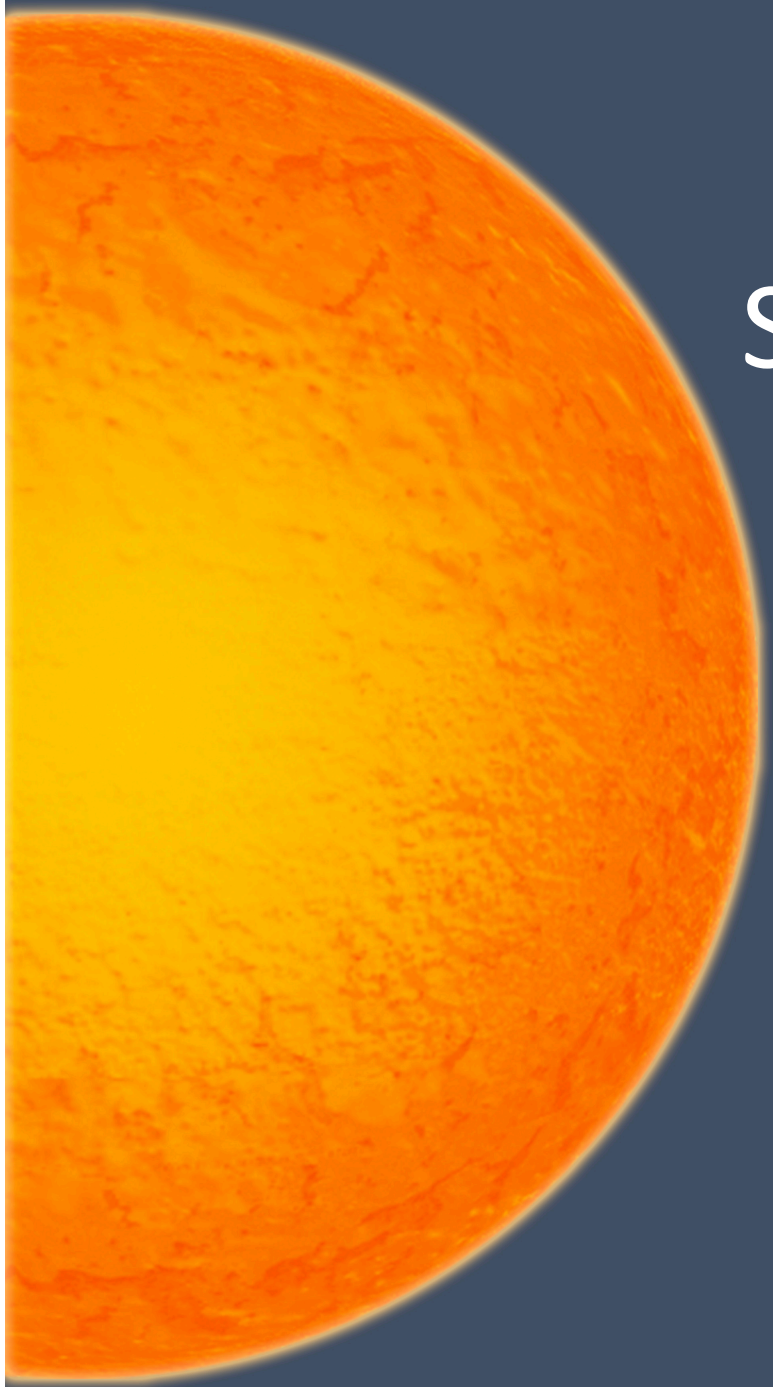


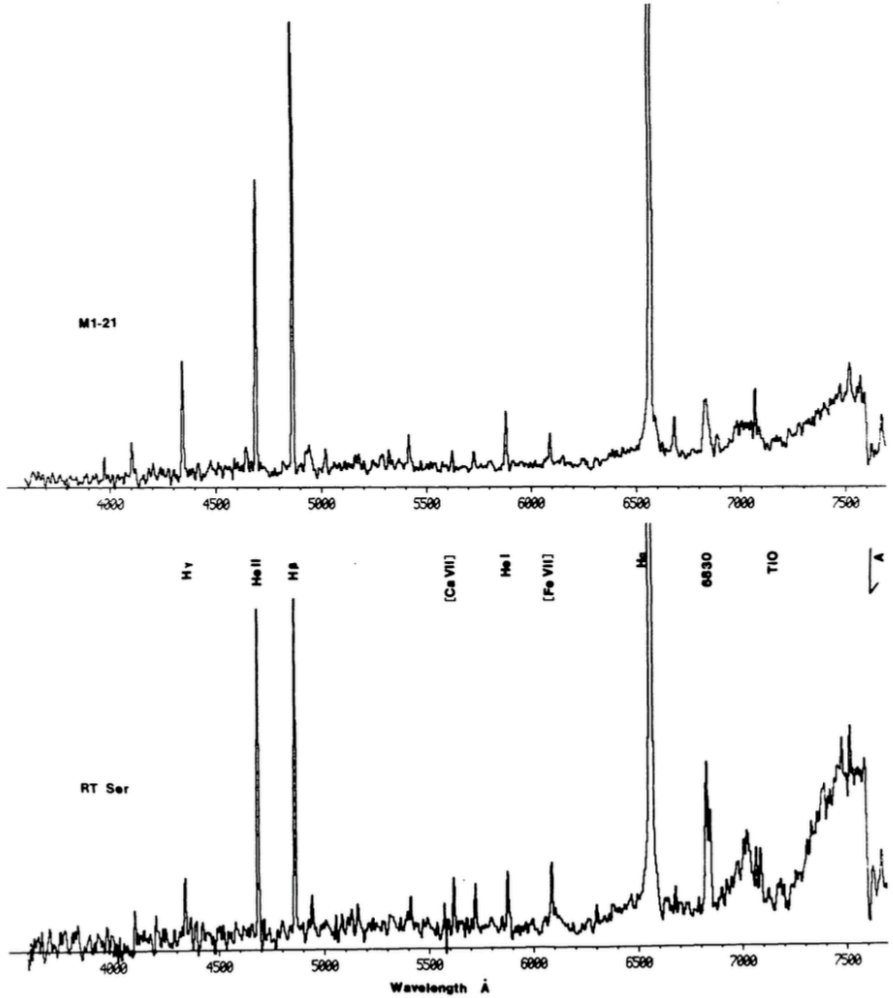
Symbiotic X-ray Binaries

K. Hinkle, R. Joyce, V. Smith (NOAO)
F. Fekel (Tenn State)
J. Mikolajewska, C. Galan
(Copernicus Inst.)
T. Lebzelter (Vienna)

Outline

1. Symbiotic binaries, the good, bad, and ugly
2. A “typical” S-symbiotic
3. Neutron star symbiotic binaries = SyXB
4. SyXB binary evolution

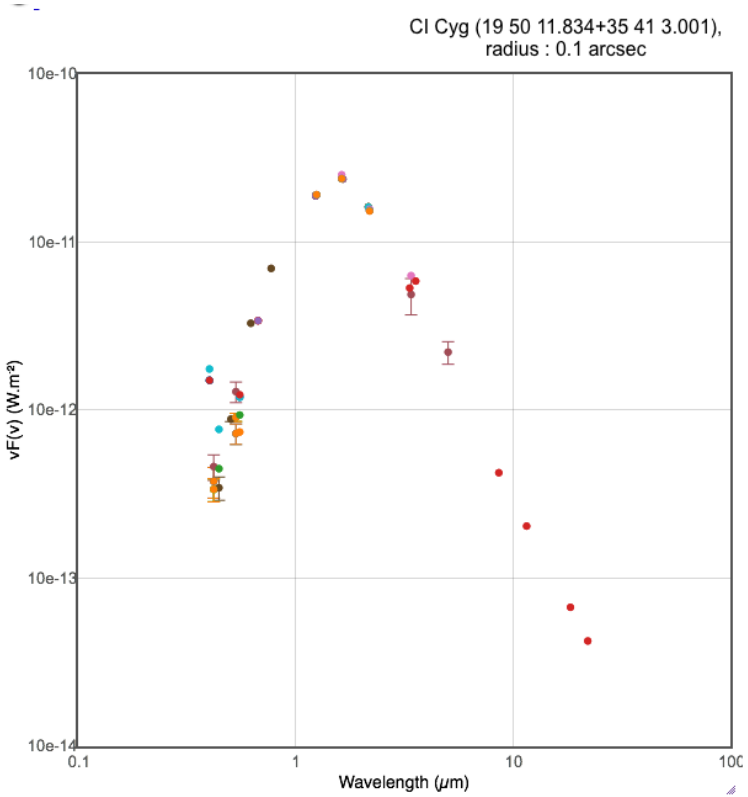
Symbiotic Stars – SySt
defined by optical spectra that combine high energy emission lines + late type giant features



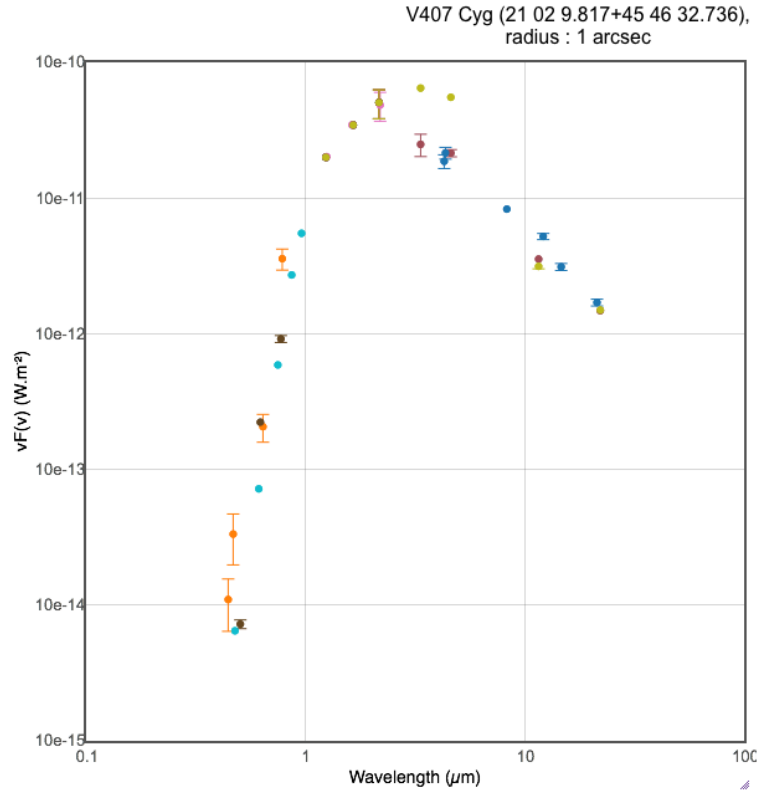
Allen 1984 ApSS 99 101

Further Divided into S and D types

S-types lack strong IR excess



D (dusty)-types are miras



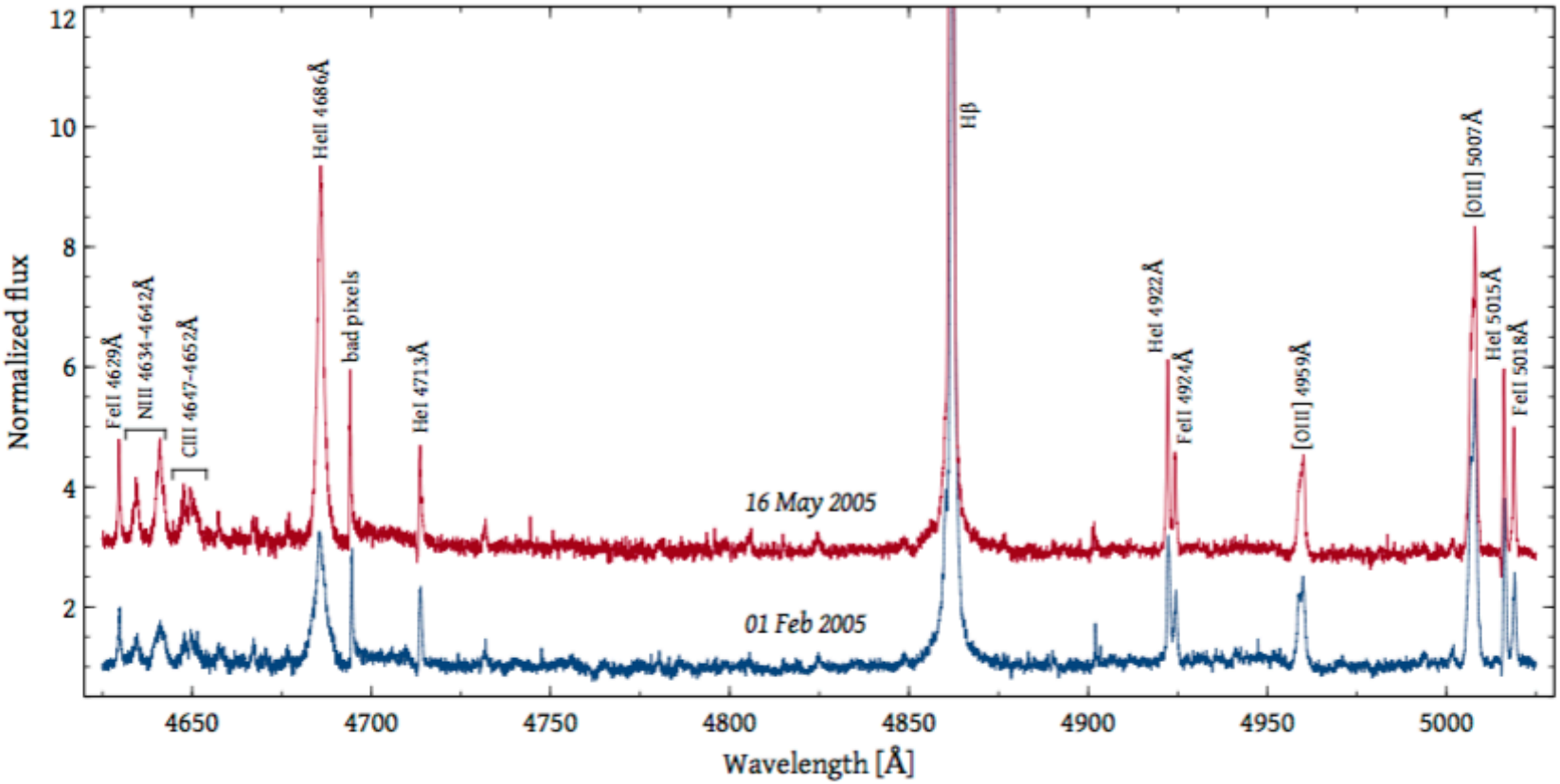
Modern understanding of symbiotic stars

One of a family of binaries consisting of a late-type star and a hot, compact, usually a white dwarf, companion

SySt class (normal symbiotic binaries) defined by:

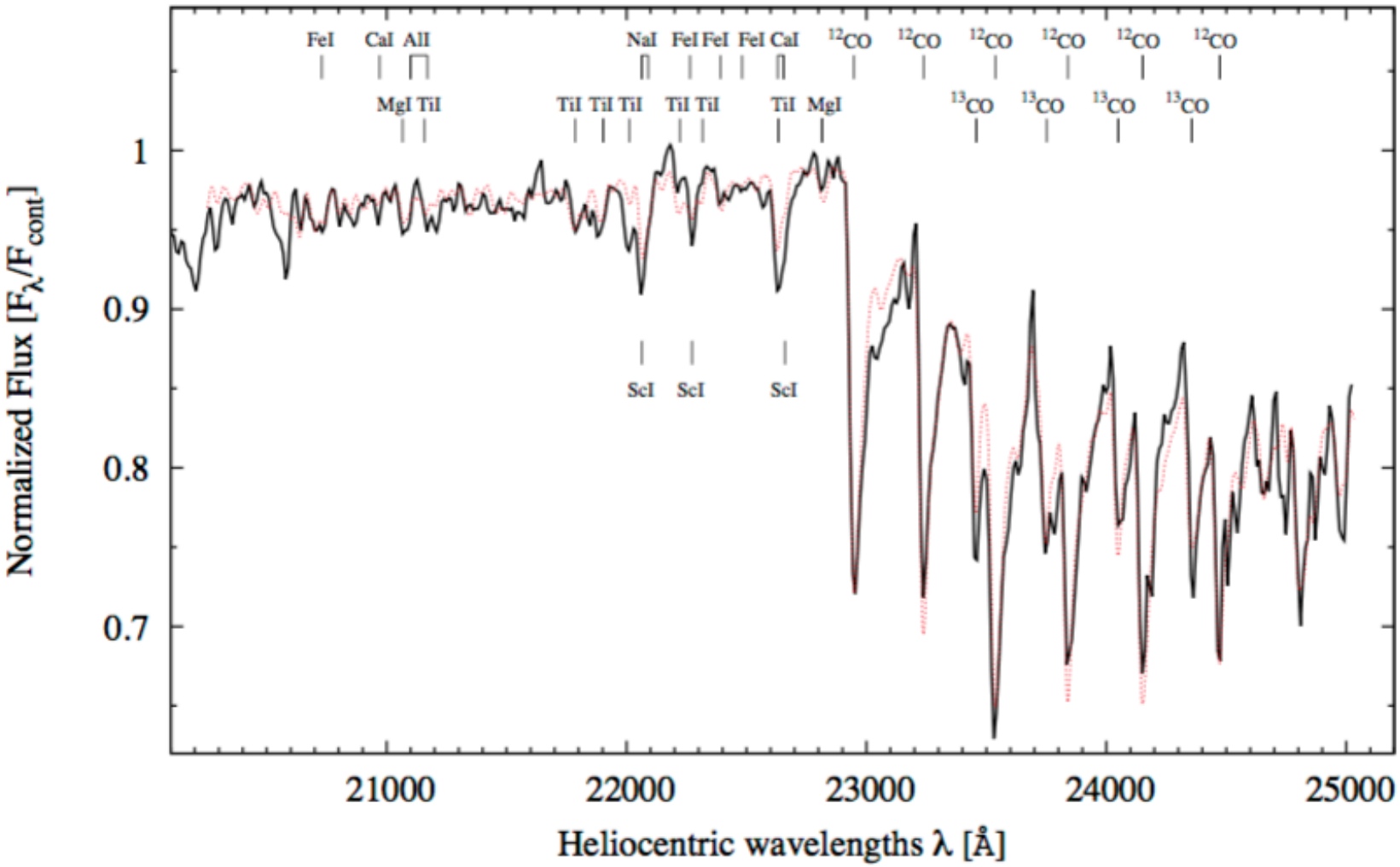
- Mass transfer
  - Generates emission line spectrum
  - Roche lobe flow to accretion disk
- Red Giant/AGB + degenerate
  - S-type: Normal M III, orbits of few years
  - D-type: Mira, orbits of decades

Emission lines – UV/Optical problem



Optical Spectrum 4600 – 5050 Å

St 2-22 - Tomov et al. 2017 Acta Astronomica 67 225



IR spectrum 2.0 – 2.5 µm

St 2-22 - Tomov et al. 2017 Acta Astronomica 67 225

IR spectra & data products

- Orbits
  - Time series of spectra spanning years to decades
  - Difficult to get the observations. TACs like short term goals.
  - IR Velocity data: Kitt Peak (coude feed, 2.1 m, 4m), Mt Stromlo 1.9 m, Fairborn 2m, Gemini South
  - 30+ orbits, Fekel, Hinkle, Joyce, et al.
- Abundances
  - IR abundance data – high resolution, high S/N, key spectral features
  - KPNO 4m/Phoenix & Gemini South/Phoenix/IGRINS
  - 20+ stars, Gałan, Mikołajewska, Hinkle, et al.

SySt = observed characteristic
<u>not unique evolutionary state</u>

- Multiple evolutionary paths converge to SySt
- Each system needs to be understood separately

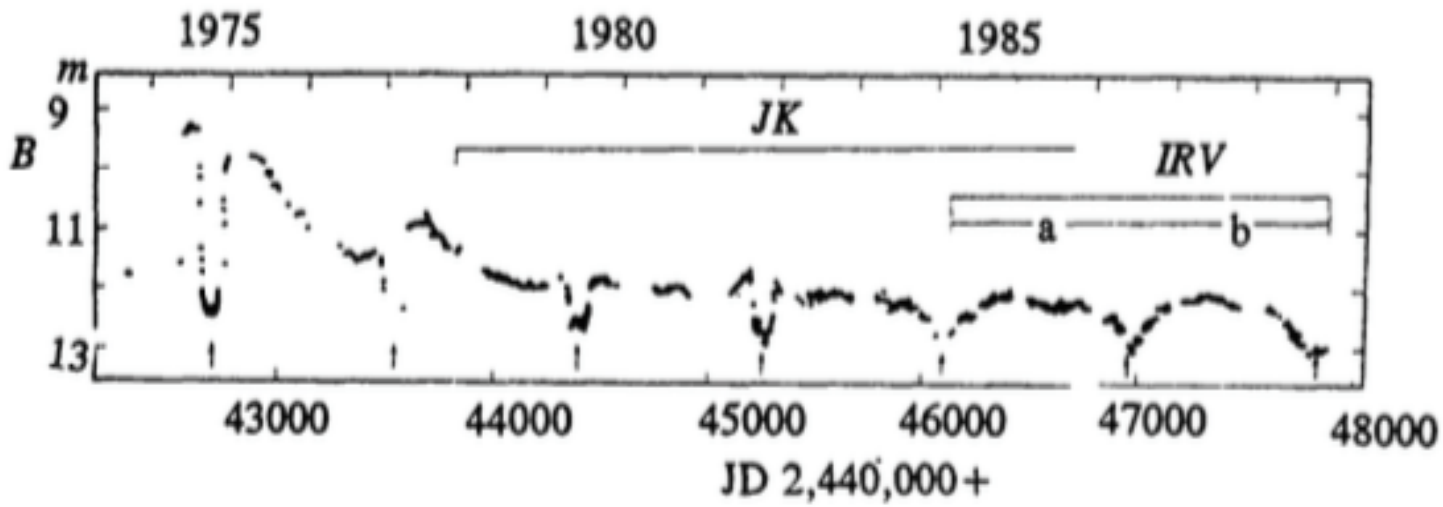
Part 2

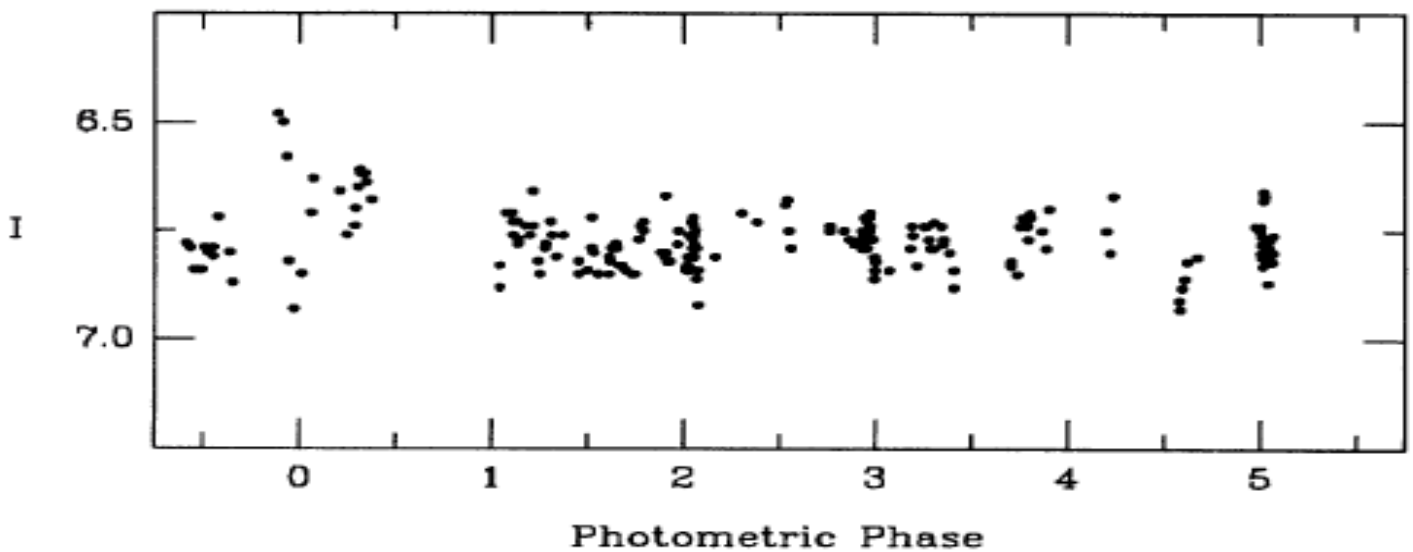
A “typical” Symbiotic

M III + white dwarf

$\therefore$ Progenitor masses both < 8 $M_\odot$

CI Cyg: M5 II + WD S-type Symbiotic photometry - WD eclipses





Eclipsing symbiotic systems common

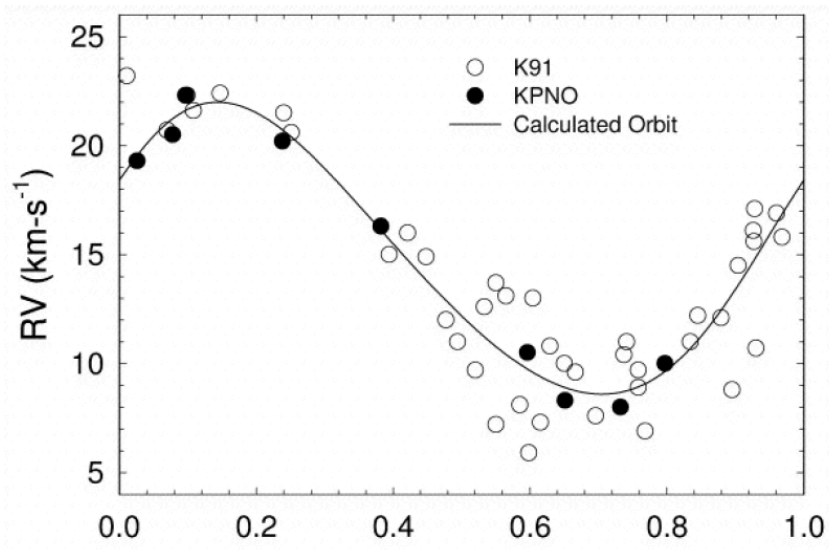
- Radius of red star is huge compared to white dwarf
- Binary eclipse criteria: $a \cos i < R_{rg} + R_{wd}$

  where a =semimajor axis

  i = inclination

  R = stellar radius

  - R_{rg} large & semimajor axis typically less than 10 R_{rg}
    ➔ large range of i that eclipses
- Duration of the eclipse a measure of R_{rg}



Fekel et al. 2000 AJ 119 1375

ORBITAL ELEMENTS OF CI CYGNI

Parameter	Kenyon et al. 1991	KPNO-Data Solution	Final Solution
P (days)	855.25 (fixed)	855.25 (fixed)	853.8 ± 2.9
T (HJD)	...	...	$2{,}450{,}426.4 \pm 59.6$
T_0 (HJD)	...	$2{,}450{,}570.4 \pm 11.2$	...
γ (km s^{-1})	18.4 ± 0.4	15.2 ± 0.3	14.96 ± 0.23
K_1 (km s^{-1})	7.0 ± 0.5	6.7 ± 0.4	6.70 ± 0.30
e	0.0	0.0	0.109 ± 0.048
ω_1 (deg)	...	...	297.7 ± 24.7
$a_1 \sin i$ (km)	$78.8 \pm 9.4 \times 10^6$	$78.9 \pm 4.7 \times 10^6$	$78.2 \pm 3.5 \times 10^6$
$f(m)$	0.027 ± 0.010	0.027 ± 0.005	0.0262 ± 0.0035

M III Radius and Mass

- Distance for Gaia and photometry ➔ $L=2261\ L_\odot$
- Spectral type M5 III ➔ $T_{eff}=3300K$
- $L=R^2T^4$ ➔ $R=145\ R_\odot$
- Red giant not Roche lobe filling = "detached"
- Pulsation Period =50 days ➔ AGB first overtone
- Pulsation theory for AGB stars:

  $\log R=(\log P+0.5\log M+1.40)/1.5$

  solve for M ➔ $2\ M_\odot$

$$f(m) = (m^3_{wd} \sin^3 i)/(m_{rg} + m_{wd})^2$$

Orbit solution: $f(m)$=0.0262

Eclipse duration -> i=73°

$M_{\text{red giant}} = 2\ M_\odot$

solve for WD mass:

$M_{\text{white dwarf}} = 0.6\ M_\odot$

From WD initial – final mass relation

MS mass was ~2 $M_\odot$

Progenitor MS binary - two similar late A stars

Part 3

Neutron star symbiotic binaries = SyXB

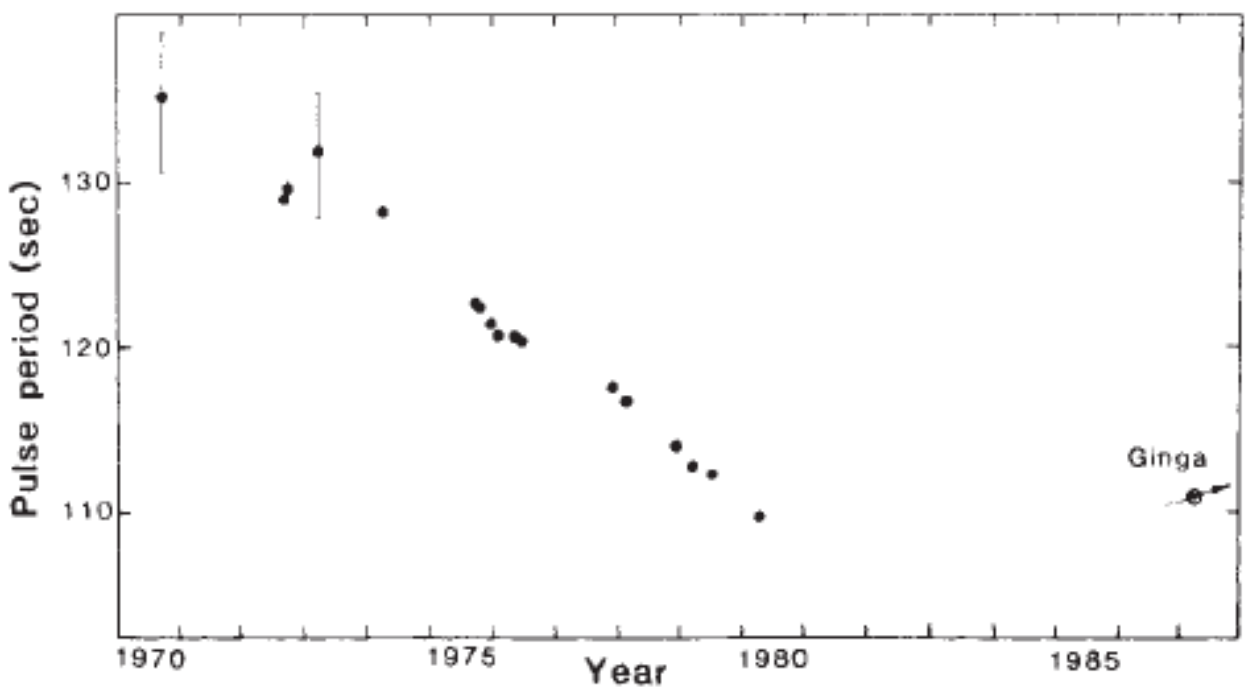
M III + neutron star

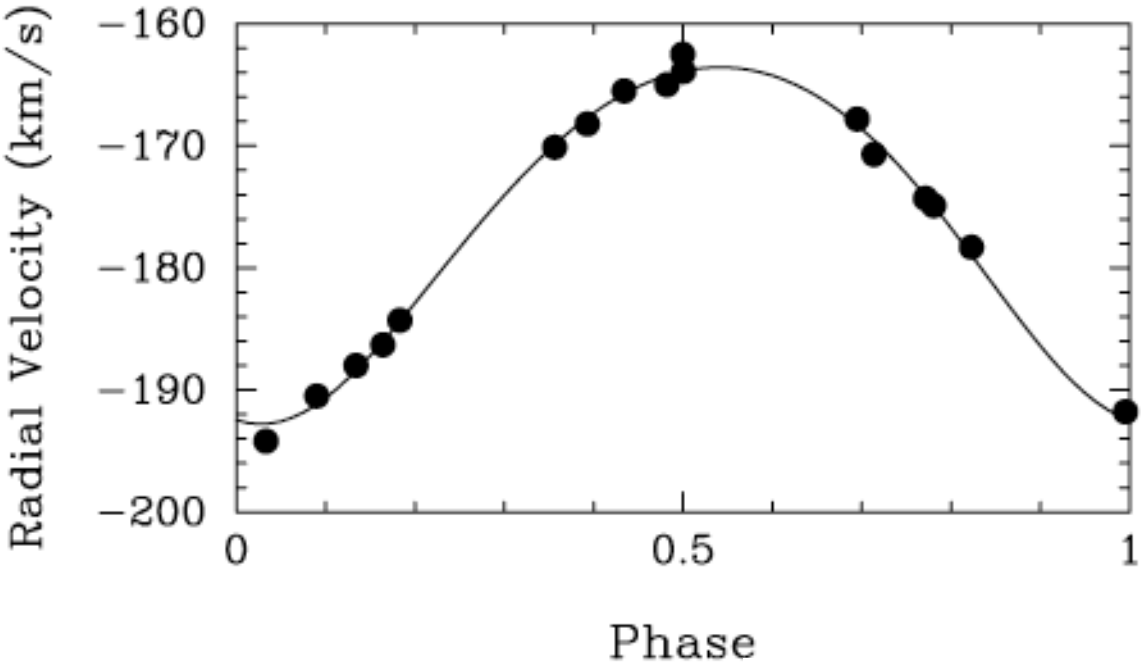
At least one star had

a progenitor $M > 8\ M_{\odot}$

Prototype (?) GX1+4=V2116 Oph

- Bright, hard X-ray source
- NS magnetic field ~ 10^{13} G
- X-ray & optical pulsar
  - Very long pulsar P ~2 minutes
  - Variations due to variable mass accretion rate





Orbital period 3.18 yrs

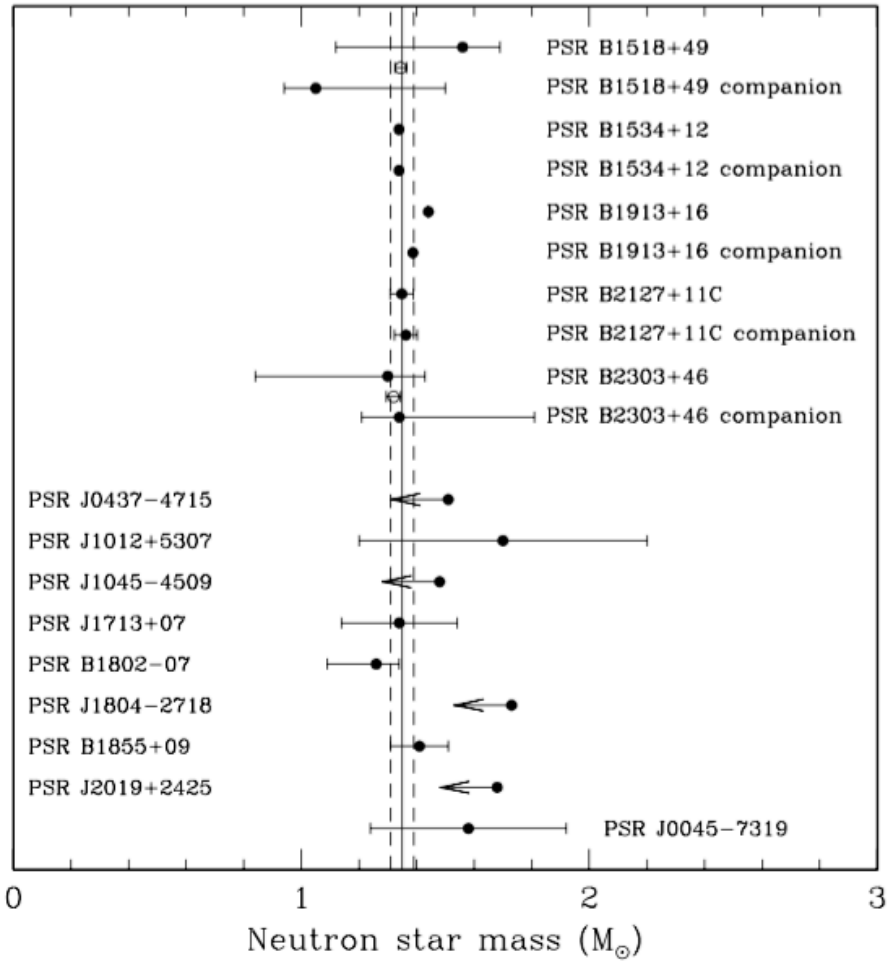
Hinkle et al. 2006 ApJ 641 479

ORBITAL ELEMENTS OF V2116 Oph

Parameter	Value
Orbital period, P (days)	1160.8 ± 12.4
Orbital period, P (yr)	3.18 ± 0.03
Time of periastron passage, T (HJD)	$2{,}451{,}943 \pm 53$
Systemic velocity, γ (km s^{-1})	-176.73 ± 0.22
Orbital velocity semiamplitude, K_g (km s^{-1})	14.62 ± 0.34
Eccentricity, e	0.101 ± 0.022
Longitude of periastron, ω_g (deg)	168 ± 17
Projected semimajor axis, $a_g \sin i$ (km)	$232.2 \pm 6.0 \times 10^6$
Projected semimajor axis, $a_g \sin i$ ($R_\odot$)	334 ± 9
Mass function, $f(m)$ ($M_\odot$)	0.371 ± 0.026
Standard error of observation of unit weight (km s^{-1})	0.85

NS mass known (?)

- $M_{NS} = 1.35 \pm 0.04\ M_{\odot}$ (at least in HMXB)



Thorsett & Chakrabary 1999
ApJ 512 288

M III Radius, Luminosity, & Mass

- Mass function large but no eclipses so

  $i \sim 70 \rightarrow M_{RG} \sim 1\ M_{\odot}$

- Using standard tricks,

  $R_{RG} = 103\ R_{\odot}$

  $L = 1270\ L_{\odot}$

- So red giant is at tip RGB or lower AGB

There must be more than one observable neutron star symbiotic. There are 50 white dwarf – neutron star binaries.

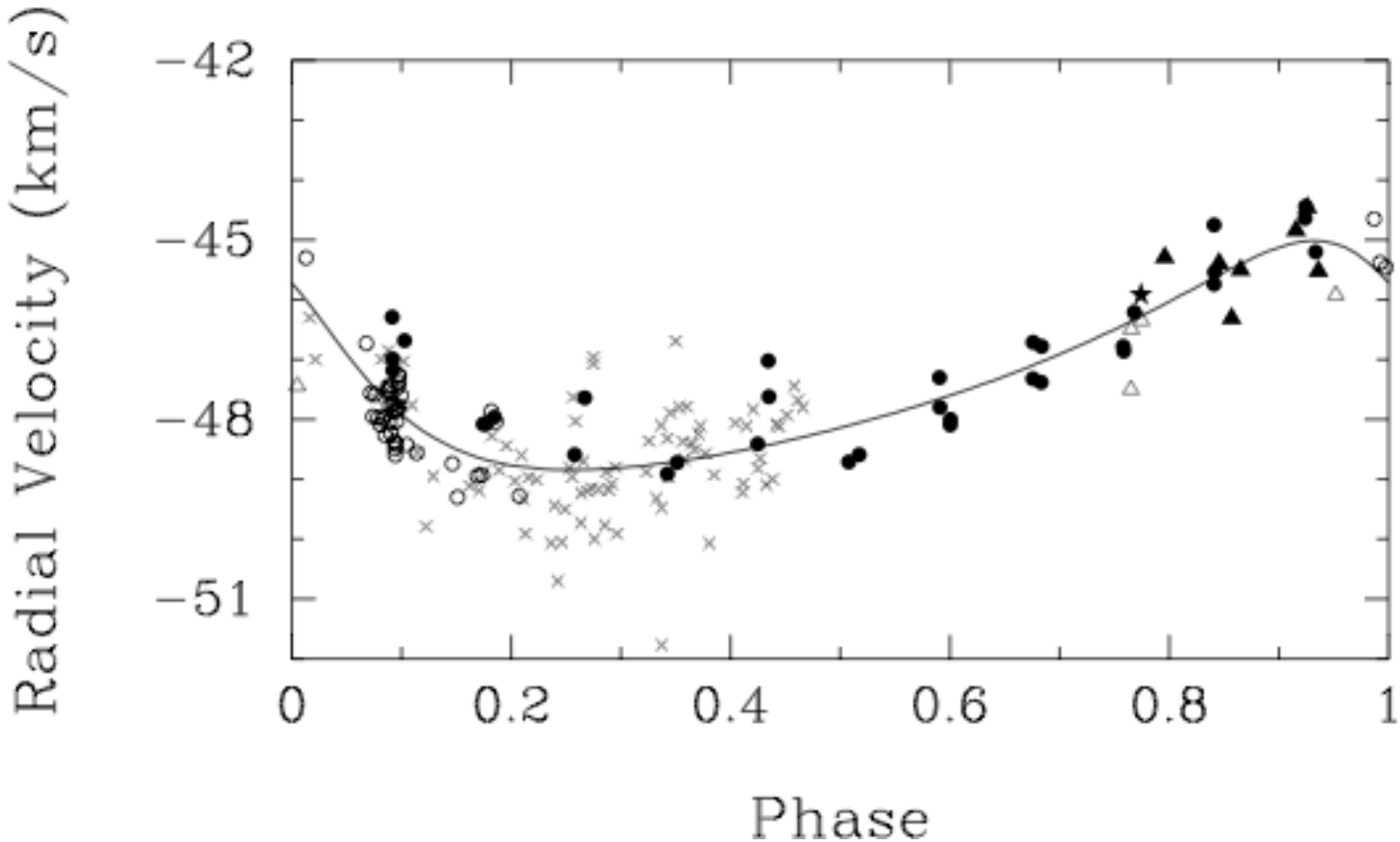
Illustration © G. Booth

8 SyXB found in recent searches

- Search for M III at X-ray coordinates
- Confirm NS with X-ray spectrum
- Optical emission spectrum is weak!
  - V2116 Oph is the exception

Masetti et al. 2006 A&A, Lü et al. 2012 MNRAS

V934 Her, P_{orb} = 12.0 yrs



Hinkle et al. in preparation

Mass, etc.

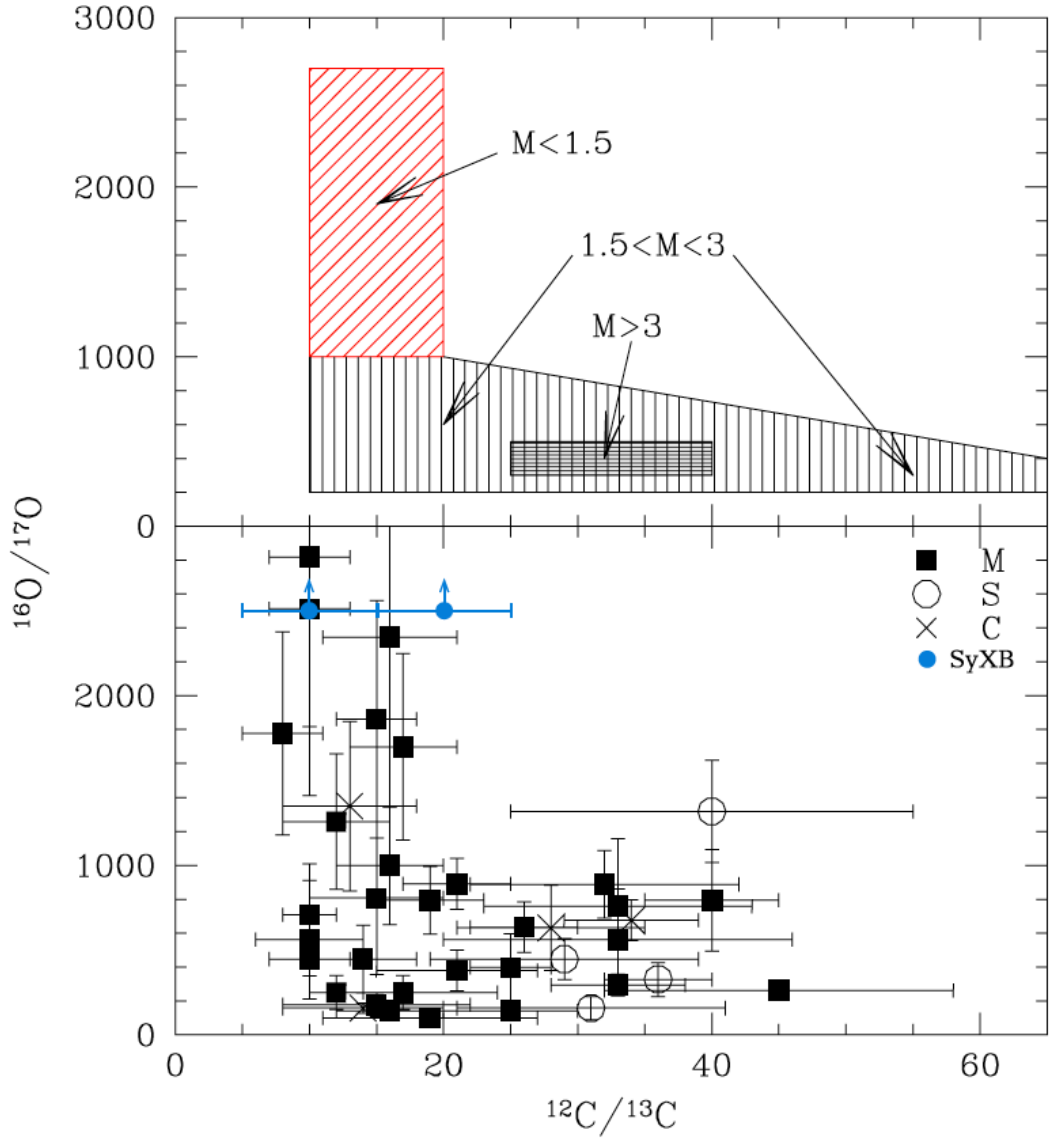
- Gaia D=544 pc, T_{eff}=3600 K, L=1800 $L_\odot$, R=110 $R_\odot$, $P_{1st\ overtone}$=44 days, and the usual tricks:
  - M_{RG}=1.2 -1.5 $M_\odot$
  - M_{NS}=1.35 $M_\odot$
- Solve for i ➔ ~11° ➔ viewing nearly pole on
  - Agrees with no pulsar detection.
- a = 813 $R_\odot$ so system is detached

Abundances

- For V2116 Oph and V934 Her we have IGRINS and Phoenix spectra
- Measured carbon and oxygen isotopes

	V934 Her	V2116 Oph
$^{12}C/^{13}C$	10±5	20±5
$^{16}O/^{17}O$	>2500	>2500
$^{16}O/^{18}O$	262±50	1000±200

First dredge up models connect MS mass to $^{12}C/^{13}C$ and $^{16}O/^{17}O$



Smith 1990, Mem Soc. Astron. Italiana 61 787

Figure from Hinkle et al. 2016 ApJ 825 38

Summary of SyXB systems

- M III progenitors were 1.0 – 1.3 $M_\odot$ stars
- M III currently:
  - ~1 $M_\odot$ (V2116 Oph)
  - 1.2 – 1.5 $M_\odot$ (V934 Her)
- M III shows no indication of either significant mass accretion or mass loss

Part 4

SyXB evolution

Constraints

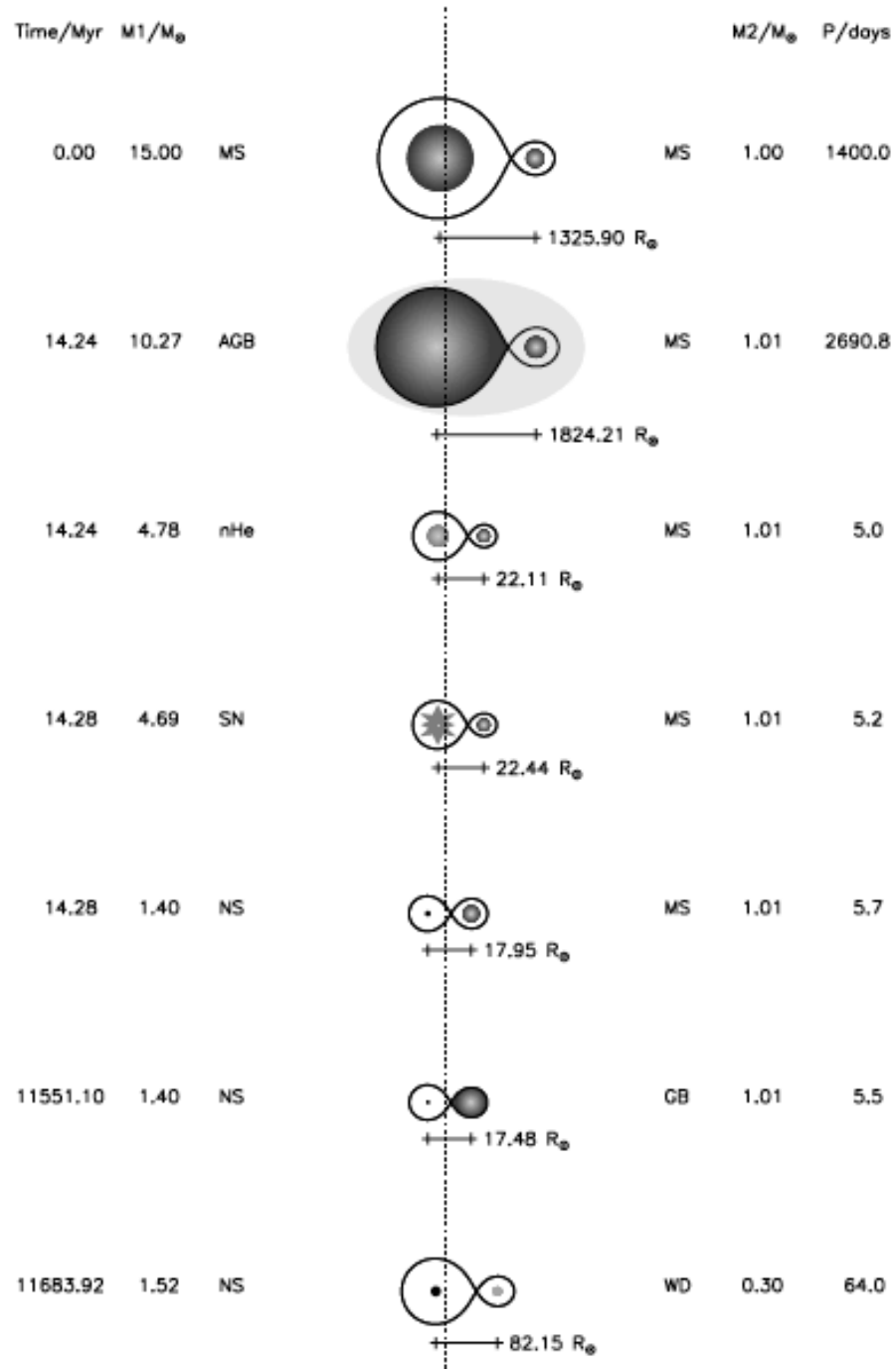
- Massive star passed through supergiant stage
  - $R_{supergiant} \sim 800\ R_{\odot}$
  - Overfills **current** Roche lobe size
  - $\therefore$ Orbit evolution
- NS from a supernova
  - CC supernova ➔ kick velocity?
  - Stripped CC supernova, less kick, mechanism?
- Low mass star now RG or early AGB star
  - Mira stage will fill current Roche lobe

Common Envelope Path

- Massive star evolves to overfull Roche lobe
- CE stage reduces mass in system
- Naked helium star ➔ type Ib/c supernova
- Produces NS with low kick velocity

PROBLEM – CE mass loss reduces orbital period from years to days

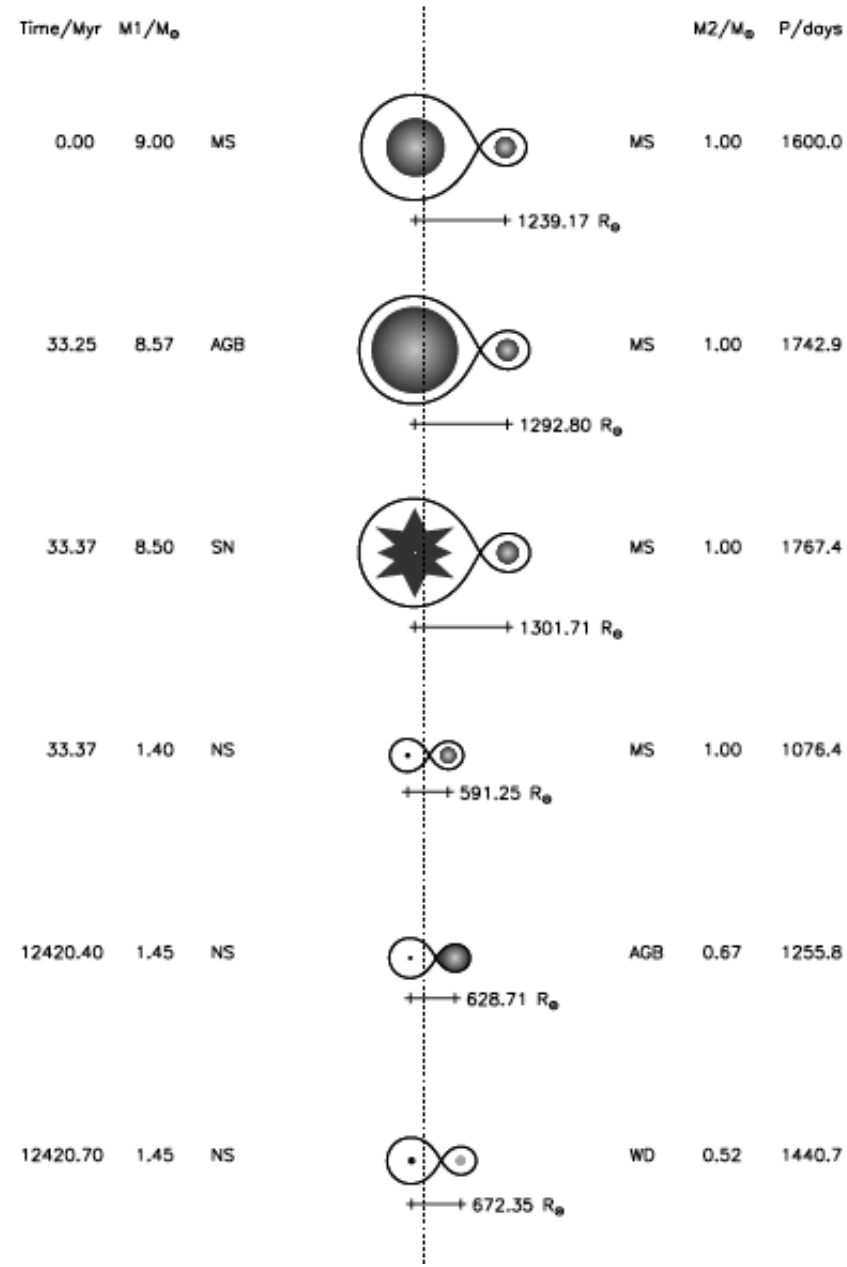
Willems & Kolb 2002 MNRAS 337 1004



CC Supernova path

- No Roche overflow of evolved massive star
- Core Collapse SN
- Survives if kick is similar to and in opposite direction from orbital velocity
- Result is MS + NS in long period orbit
- Mass transfer during Mira stage spins up NS and expands RL size
- End product is NS + WD long period binary

Willems & Kolb 2002 MNRAS 337 1004



Work in Progress

- Additional SyXB orbits unlikely using open access telescopes
  - Orbits require decade long time series of spectra
- Abundance work in progress – IGRINS
  - M III progenitor mass
  - Progenitor population
  - Traces of SN?


The End